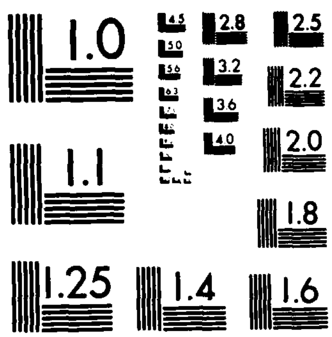
AD-A174 751 FUNDAMENTAL STUDY OF JET FLOWS(U) NIELSEN ENGINEERING AND RESEARCH INC MOUNTAIN VIEW CA D NIXON 30 JUN 86 NEAR-TR-364 AFOSR-TR-86-2051 F49620-85-C-0055 1/1

UNCLASSIFIED F/G 20/4 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A174 751

AFOSR-TR- 86-2051

FUNDAMENTAL STUDY OF JET FLOWS

by

David Nixon

NIELSEN ENGINEERING
AND RESEARCH, INC.

OFFICES: 510 CLYDE AVENUE / MOUNTAIN VIEW, CALIFORNIA 94043 / TELEPHONE (415) 968-9457

86 11 25 853

COPY NO. 1 ②

AFOSR-TR- 86-2051

FUNDAMENTAL STUDY OF JET FLOWS

by

David Nixon

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEAR TR-364	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 86-2051
6a. NAME OF PERFORMING ORGANIZATION Nielsen Engineering & Research, Inc. 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR, Directorate of Aerospace Sciences
6c. ADDRESS (City, State, and ZIP Code) 510 Clyde Avenue Mountain View, CA 94043-2287	7b. ADDRESS (City, State, and ZIP Code) Building 410 Bolling AFB, D.C. 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-85-C-0055
8c. ADDRESS (City, State, and ZIP Code) AFOSR/NA Bolling AFB, DC 20332	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2307; TASK NO. A1; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Fundamental Study of Jet Flows (U)

12. PERSONAL AUTHOR(S)
David Nixon

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Report	FROM 3/01/85 TO 6/30/86	June 30, 1986	6

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Jet Flows,
20	04		Turbulence

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The physics of some problems that arise in impinging jet flows have been investigated using a Very Large Eddy Simulation (VLES) of the Navier-Stokes equations. The problems that have been examined include the upwash fountain covered by the collision of two walljets, possible causes of a Reynolds number scaling in the suck down phenomena and possible flow resonance. The effects of heat were also studied. It was found that the VLES technique can help explain certain aspects of jet flows.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL ~~David Nixon~~ DR JAMES D WILSON	22b. TELEPHONE (Include Area Code) ~~(415) 968-94~~57 22c. OFFICE SYMBOL NA

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

202-767-4935

NEAR TR 364

FUNDAMENTAL STUDY OF JET FLOWS

David Nixon
510 Clyde Avenue
Mountain View, CA 94043-2287

June 30, 1986

Final Report for Period 1 March 1985 - 30 June 1986

Distribution Unlimited

Prepared for

AFOSR
Directorate of Aerospace Sciences
Building 410
Bolling AFB, D.C. 20332-6448

APPENDIX

for

Fundamental Study of Jet Flows

NEAR TR-364

Contract F49620-85-C-0055
Air Force Office of Scientific Research

Nielsen Engineering & Research, Inc.
510 Clyde Avenue, Mountain View, CA 94043-2287

COMPUTER CODE

The computer code used in the investigation, which is described in References 1 and 2, uses the implicit/explicit method of MacCormack (Reference 3) and a cartesian grid. Several different turbulence models are used, depending on the application. In some of the studies, where only averaged quantities are of interest, a k-ε model is used whereas for the Very Large Eddy Simulations (VLES) a vorticity model is used for the subgrid scales. The VLES method resolves the largest scales in the flow and is therefore a time dependent calculation. The method is ideally suited to the present range of problems because the jet flows are dominated by the streamwise velocity component which has a peak in the turbulent kinetic energy spectrum at a lower wave number than the other components. This means that a relatively coarse grid will resolve a reasonable portion of the large energy containing eddies.

SPREADING RATE OF THE FOUNTAIN

In this problem two, two-dimensional wall jets colliding with each other are modeled. At the jet exits a suitable representation of the turbulence is used and this is validated by comparing computed Reynolds stresses for an isolated wall jet with experimental data. The VLES calculation did produce the increased spreading rate compared with an averaged calculation. The mechanism of the enhanced spreading rate is that eddies of different kinetic energy collide and thus the high energy eddy will push through the opposing flow before being deflected upwards in the fountain. In an averaged calculation all of the colliding eddies have the same energy and hence do not push through the opposing flow but are deflected upwards about the plane of symmetry. This work is reported in Reference 2.

The accuracy of the explanation of the increased spreading rate given above is enhanced by the results of two series of calculations, namely the introduction of heat into one jet as a tracer and the introduction of a fence at the center of the collision zone of the two jets. The VLES technique is used in these studies.

In Figure 1 the results given by heating the right wall jet are shown. The figure shows the location of the hot gas, at some instant and it can be seen that, the fluid from the right hand jet has crossed the centerline. Further evidence can be seen in Figure 2 where instantaneous streaklines are shown. The streaklines in both Figure 2a and Figure 2b are at a location corresponding to the wall jet thickness. In Figure 2a the streaklines from the left hand jet are shown and in Figure 2b those from the right hand jet are shown. It can be seen that the fluid from the right hand jet has propagated further past the centerline than that from the left hand jet, corroborating the results of the heated jet case shown in Figure 1.

If the mechanism for the increased spreading rate is that given above then the introduction of a fence, at the centerline, should reduce the spreading rate since fluid from the jets is inhibited from crossing the centerline until the top of the fence. Mach number contours for flows with and without the fence are shown in Figure 3 and velocity vectors are shown in Figure 4. It can be seen that the presence of the fence reduces the spreading rate of the fountain considerably.

EFFECTS OF HEAT

As part of the contract the effect of temperature on the flow of an impinging jet was examined numerically. In these calculations the jet was at a temperature of 1008 degrees K and the ambient air is at 288 degrees K. The jet is exhausting into a crossflow. The object is to detmine the effect of temperature on the shape of the ground vortex in the belief that this is a fairly critical parameter in such flows. The calculations are a standard version of a high Reynolds number k-ε turbulence model for a variable density flow described by Viegas and Rubesin (Reference 4); wall functions are used. The turbulent kinetic energy, k, and the disappation rate, ε, are given by the following equations. The turbulent coefficient of viscosity is denoted by μ_T. The molecular viscosity is temperature dependent and satisfies Sutherlands law.

$$\mu = \bar{\rho}\, c_\mu\, k^2/\varepsilon$$

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i}(\rho k U_i) + \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right) = S_k$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x_i}(\rho \varepsilon U_i) + \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right) = S_\varepsilon$$

$$S_k = P_k - \rho\varepsilon; \quad P_k = \mu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)$$

$$S_\varepsilon = C_1 \frac{\varepsilon}{k} P_k - \frac{C_2 \rho \varepsilon^2}{k}$$

$$C_\mu = 0.09 \quad C_1 = 1.44 \quad C_2 = 1.92$$

$$\sigma_k = 1 \quad \sigma_\varepsilon = 1.3$$

Two runs with different temperatures but with similar levels of turbulent kinetic energy at the jet were made and very little effect of jet temperature was observed. It should be noted that variable density turbulence models have not been tested as adequately as those for incompressible flow and therefore some reservation should be attached to the present conclusion.

REYNOLDS NUMBER SCALING OF THE SUCK DOWN EFFECT

It has been observed that small scale experiments do not produce the suck down effect of a full scale test. The reasons for the discrepancy are not known although there are several candidate explanations, such as Reynolds number effects or initial turbulence levels on the jet. The present investigation is concerned with possible Reynolds number effects.

The difference between flows at different Reynolds number is the range of turbulence scales and the VLES method is reasonably well suited to modeling a range of scales. In a VLES calculation the subgrid scale eddies are modeled by a simple vorticity turbulence model and the eddy size that is resolved is related to the grid size. If a comparison of flows at two different Reynolds numbers is to be made the effect of the range of scales is captured only if the size of the eddies resolved has the same relation to the dissipation length scale in both cases.

The filtered and Reynolds averaged momentum equation used in the VLES calculation is

$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial \bar{U}_i \bar{U}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{R_e}\frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} - \frac{\partial \overline{\tilde{U}_i' \tilde{U}_j'}}{\partial x_j}$$

$$-\frac{1}{3}\frac{\partial \bar{Q}_{kk}\delta_{ij}}{\partial x_j} - 2\left(\frac{C_s \Delta}{\ell}\right)^2 \frac{\partial}{\partial x_j}\left(|S| S_{ij}\right) \qquad (1)$$

where an overbar denotes a Reynolds averaged quantity and a tilde denotes a quantity that is resolved by the grid. The analysis leading to this equation is similar to that given by Moin & Rogallo (Reference 5). The flow quantities are scaled to jet exit or ambient air values and the boundary conditions for the impinging jet problem are invariant with Reynolds number. If it is assumed that the effect of molecular viscosity is negligible then the only Reynolds number effect is in the subgrid scale term

$$\left(\frac{C_s \Delta}{\ell}\right)^2$$

where C_s is a constant and Δ is the characteristic size of the resolvable eddies. If the size of the resolved scale to the Kolmogorov scale is kept constant then calculations for two different Reynolds numbers will model the difference in the range of scales.

The Kolmogorov length scale, η, is given as

$$\eta = \left(\frac{U^3}{\ell \nu^3}\right)^{\frac{1}{4}}$$

where U is a characteristic velocity of the turbulence, ℓ is a characteristic length of the energy containing eddies and ν is the kinematic viscosity. The characteristic velocity can be taken to be the velocity of the jet and the characteristic length of the energy containing eddies can be taken to be the VLES resolvable grid size Δ, since Δ will be at a particular point on the turbulent kinetic energy spectrum. Thus, in order to represent the range of scales, the ratio

$$\frac{\Delta}{\eta} = \left(\frac{U\Delta}{\nu}\right)^{3/4}$$

must be a constant. Hence

$$\frac{U\Delta}{\nu} = \text{constant}$$

If the Reynolds number is changed by changing only ν then the grid size is inversely proportional to the Reynolds number. Thus if the Reynolds number is doubled the grid size is halved.

Calculations for Reynolds numbers of 20,000, 40,000 and 60,000 were performed for the configuration shown in Figure 5, namely two wall jets colliding.

Since the grid size, Δ, in Equation 1 is multiplied by the constant C_s the calculations used the same grid which makes the truncation error uniform, and changes C_s in inverse proportion to the Reynolds number.

The results for the total entrainment are given below.

Re:	20,000	40,000	60,000
Entrainment:	0.345	0.419	0.370

It can be seen that there is an effect of Reynolds number for Reynolds numbers of this order of magnitude.

STUDIES OF FLOW RESONANCE

This investigation was undertaken to determine if the VLES technique could model flow resonance such as that studied by Ho and Nossier (Reference 6). The flows considered are variations on a circular jet impinging on a ground plate. The height/jet diameter ratio is 3.1 and the nominal jet Mach number is 0.9. The jet exits out of a top plate. The jet has a constant stagnation pressure.

The first flow is with the ground plate removed, in other words, a free jet. The pressure near the jet centerline approximately 3 jet diameters down from the jet exit is shown in Figure 6 as a function of time. It can be seen that the pressure does oscillate periodically with time. In order to determine if there is a characteristic Strouhal number the fluctuating pressure was

Fourier transformed to give $\hat{p}$ and the power spectrum plotted against the Strouhal number (St), fD/U_{jet}, where f is the frequency and D is the jet diameter. In Figure (7) the power spectrum, G, of the pressure fluctuations, given by

$$G = |\hat{p}|^2$$

It can be seen that there is a peak at a Strouhal number of about 0.45.

The second flow is for the impinging jet and in Figure (8) the pressure oscillations close to the ground can be seen. The power spectrum is shown in Figure (9) and does not have a spike at the Strouhal number of 0.45 but the general behavior is not as pronounced as in the free jet.

Finally, an attempt to model more closely the experiments of Ho and Nossier was made by making the top wall mimic the presence of the nozzle structure. Results are shown in Figures (10) and (11). It can be seen that the pressure does fluctuate as in the previous case but power spectrum is considerably different. However, there is little agreement with the results of Ho and Nossier.

It can be concluded from these results that the VLES method can represent resonant flows. However, the quality of the results need to be improved before the method can be considered a useful research tool.

REFERENCES

1. Childs, R. E. and Nixon, D.: Simulation of Impinging Turbulent Jets, AIAA paper 85-0047, 1985.

2. Childs, R. E. and Nixon, D.: Unsteady Three-dimensional Simulation of a VTOL Upwash Fountain, AIAA paper 86-0212, 1986.

3. MacCormack, R. W.: A Numerical Method for Solving the Equations of Compressible Viscous Flow, AIAA paper 81-0110, 1981.

4. Viegas, J., Rubesin, M.: Wall Function Boundary Conditions for the Solution of the Navier Stokes Equations for Complex Compressible Flows, AIAA paper 83-1694, 1983.

5. Rogallo, R., Moin, P.: Numerical Simulation of Turbulent Flows. Annual Review of Fluid Mechanics, Vol. 16, pp. 99-137, 1984.

6. Ho, C. M. and Nossier, N. S.: Dynamics of an Impinging Jet Part I. The Feedback Phenomena, J. Fluid Mech., Vol. 105, pp. 119-142, 1981.

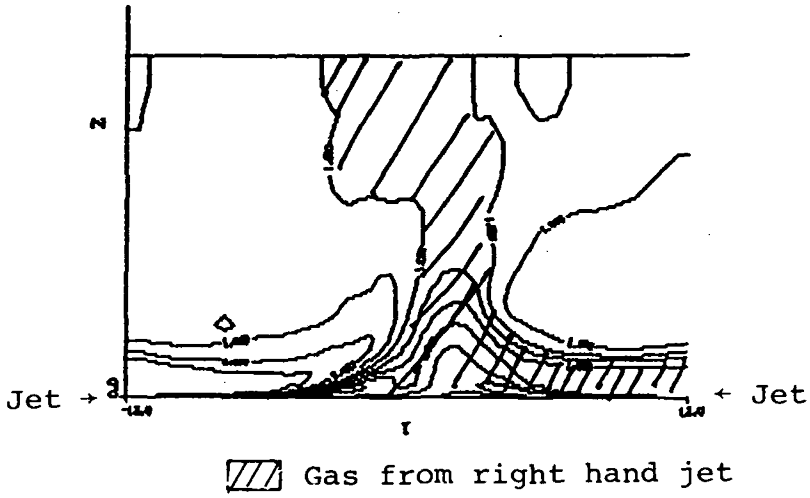


Figure 1.- Use of Heat as a Tracer for Jet Flows.

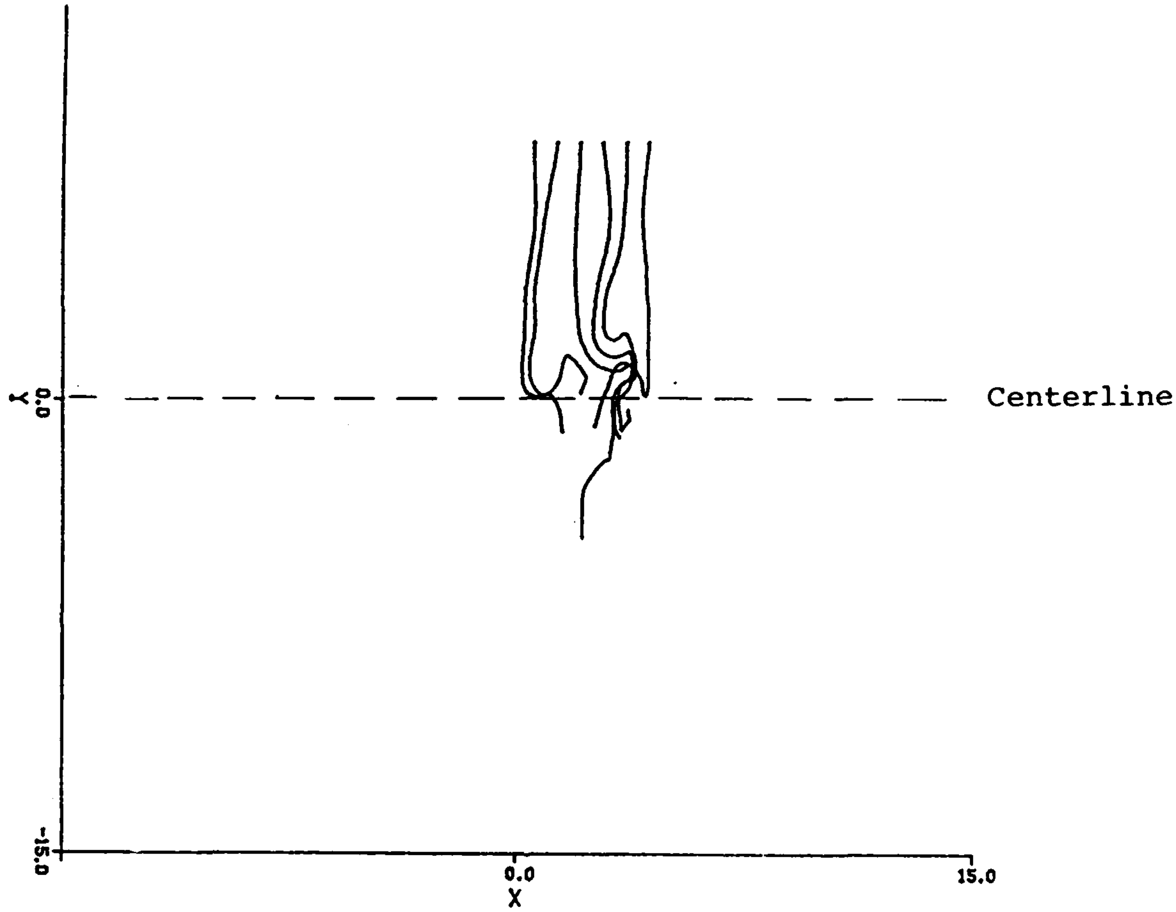


Figure 2a.- Streaklines for the Left Hand Jet.

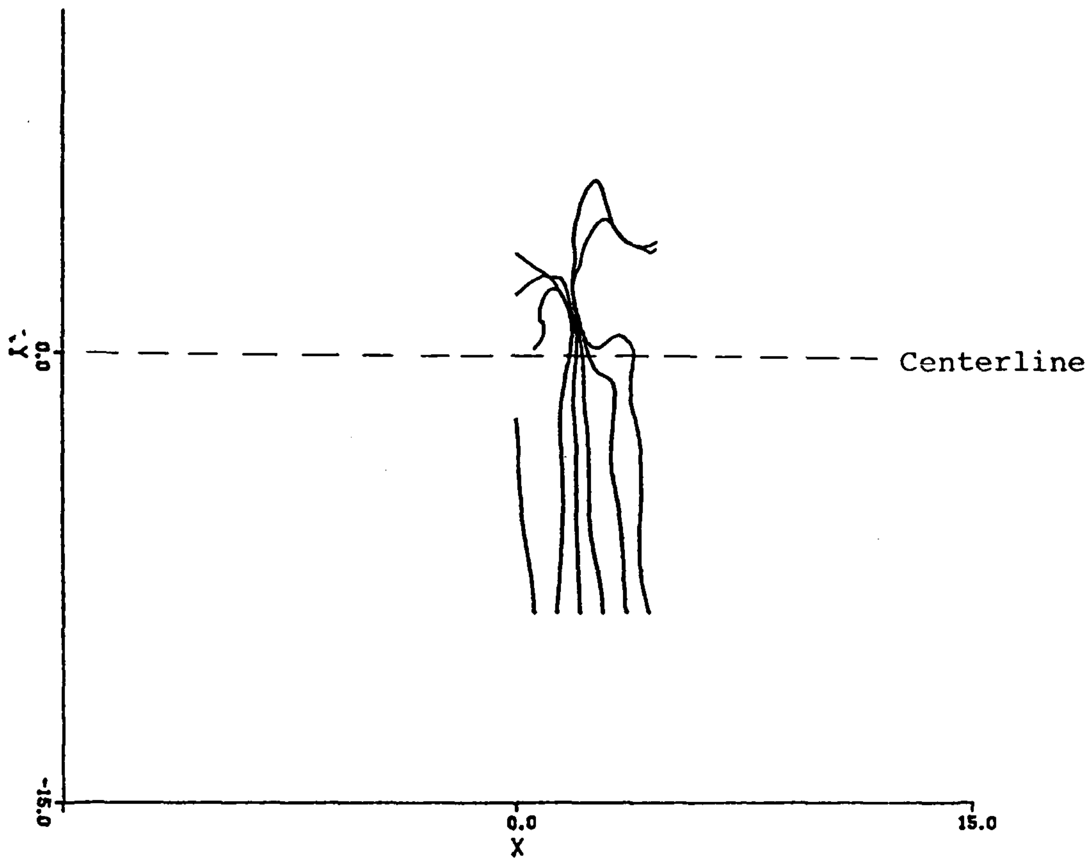


Figure 2b.- Streaklines for the Right Hand Jet.

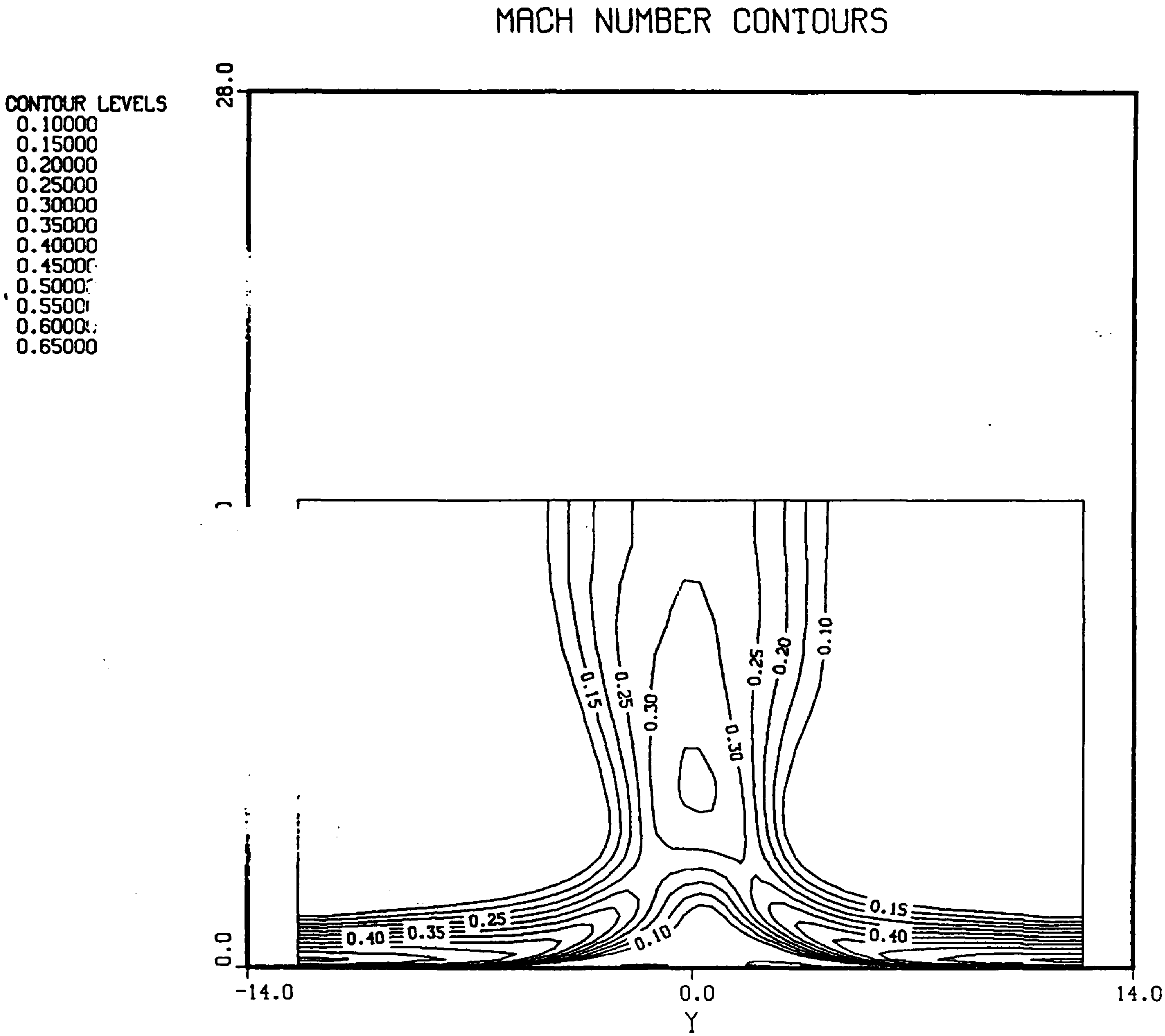


Figure 3a.- Mach Number Contours for Jet without a Fence.

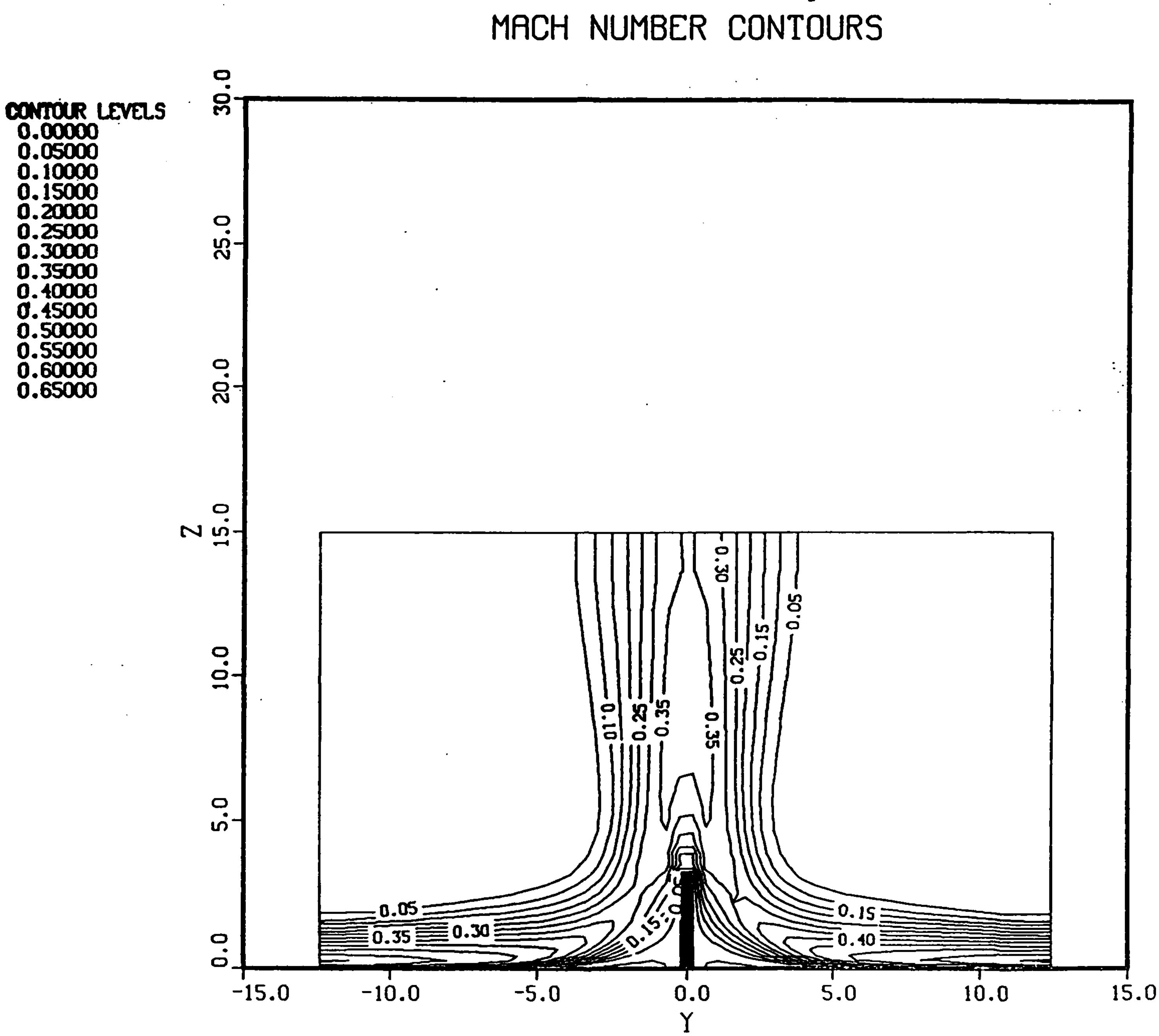


Figure 3b.- Mach Number Contours for Jet with a Fence.

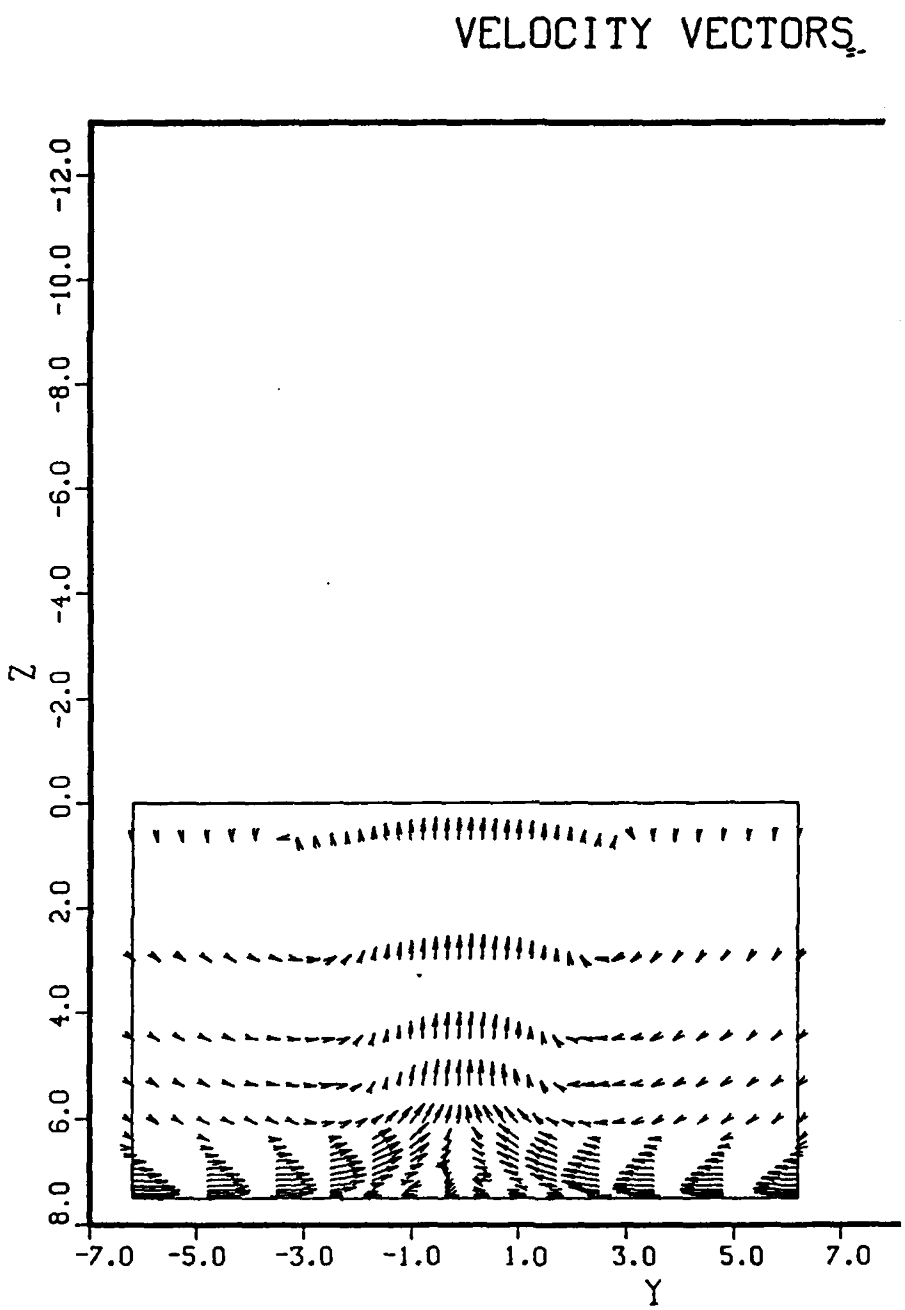


Figure 4a.- Velocity Vectors for Jet without Fence.

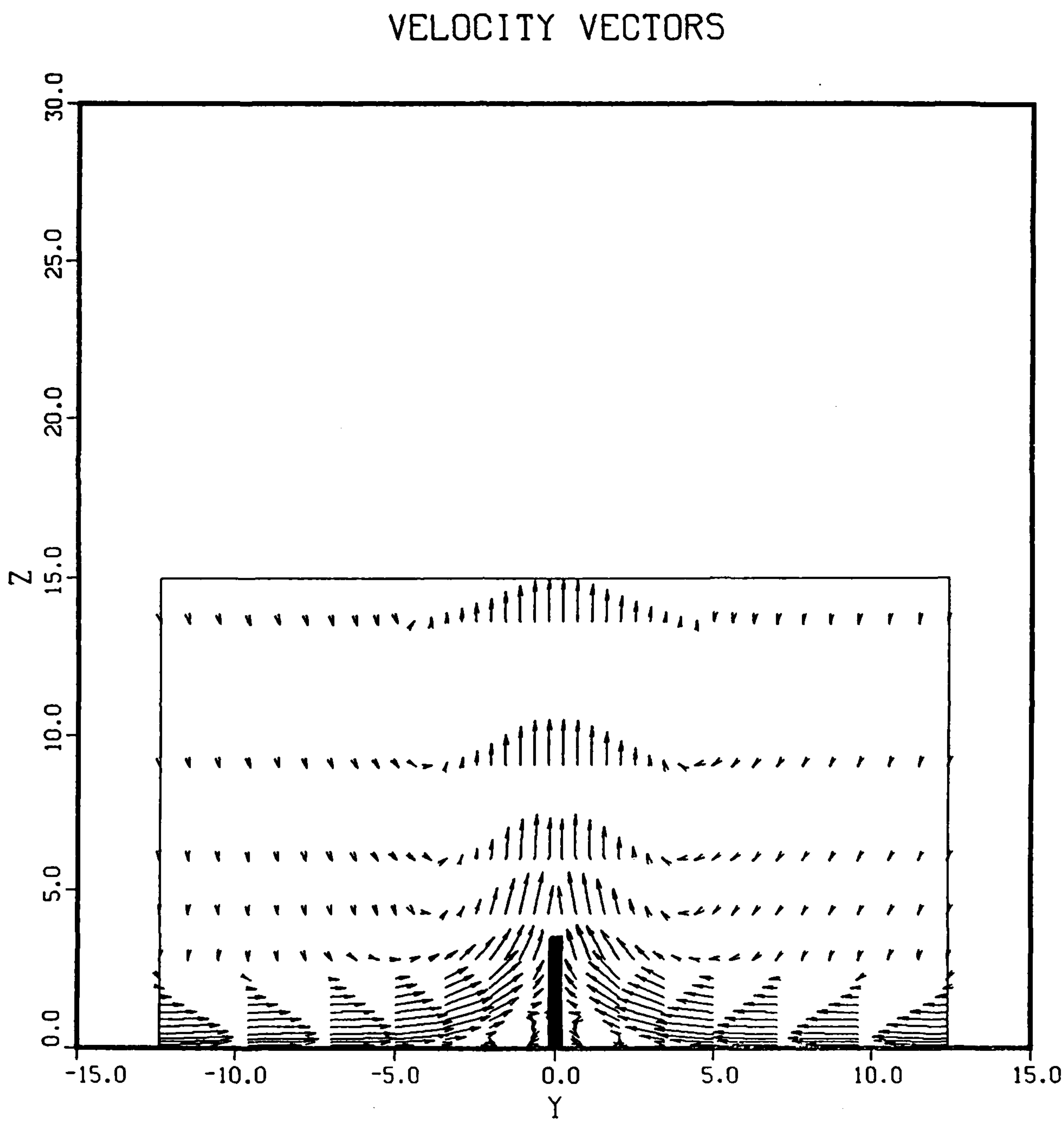


Figure 4b.- Velocity Vectors for Jet with a Fence.

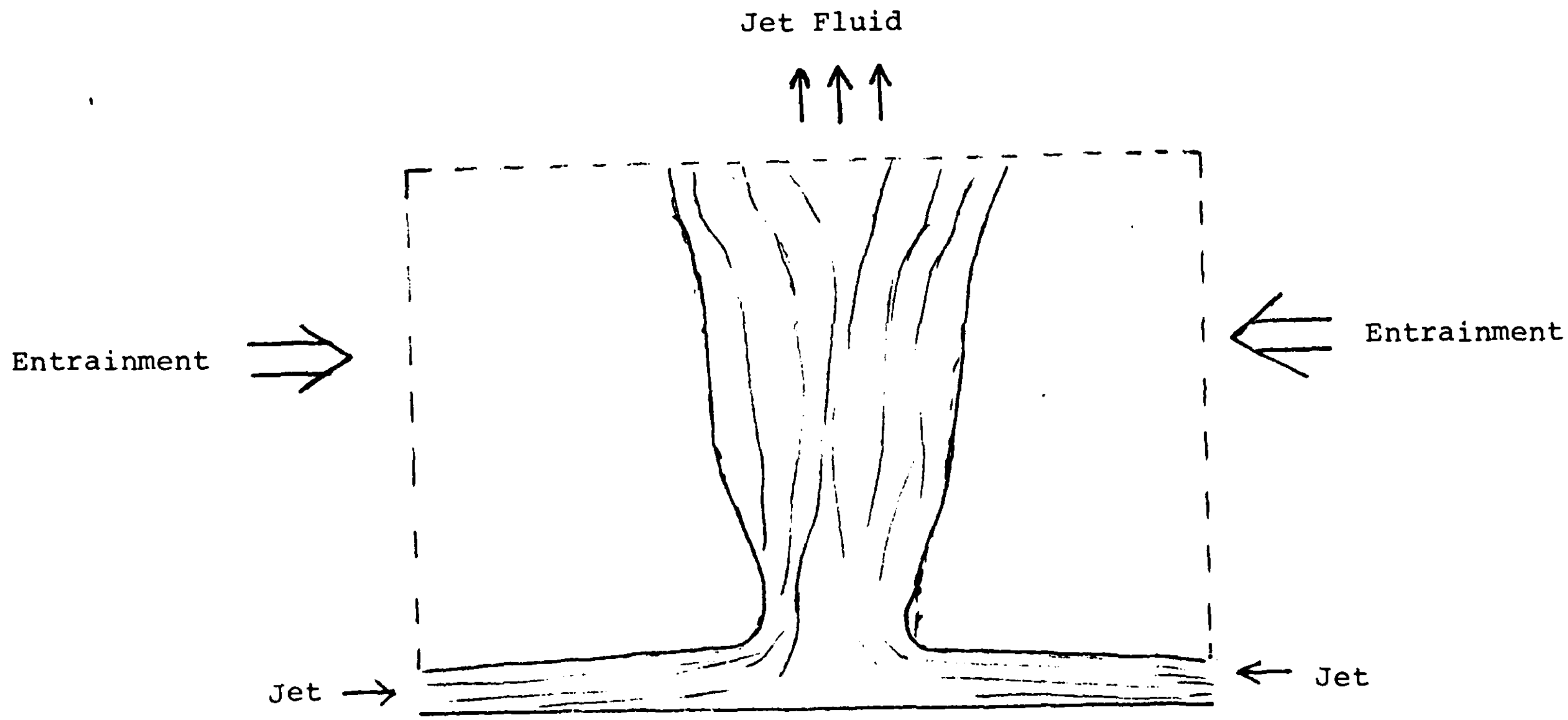


Figure 5.- Sketch of Jet Configuration for Suck Down Study.

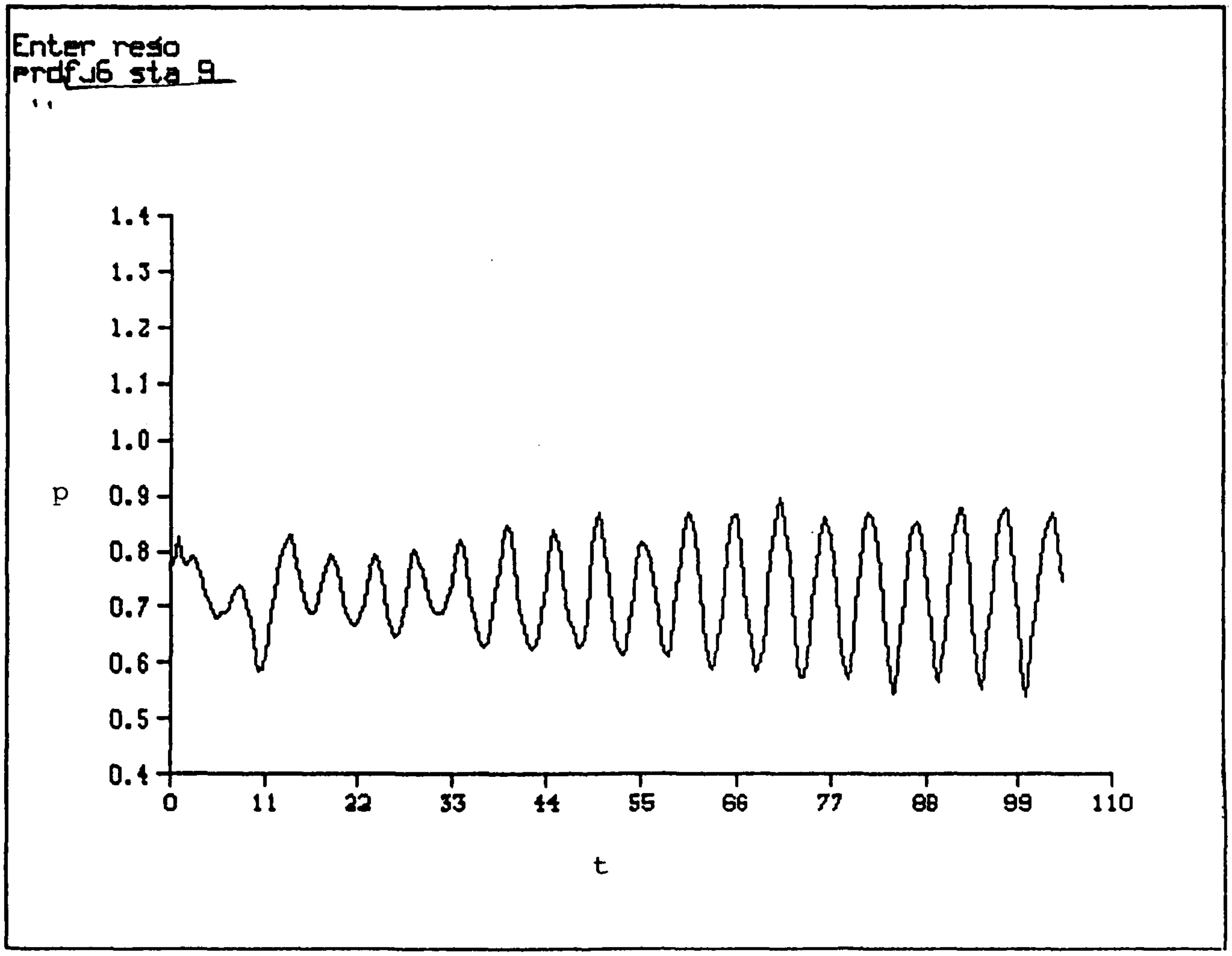


Figure 6.- Variation of Pressure with Time (Free Jet).

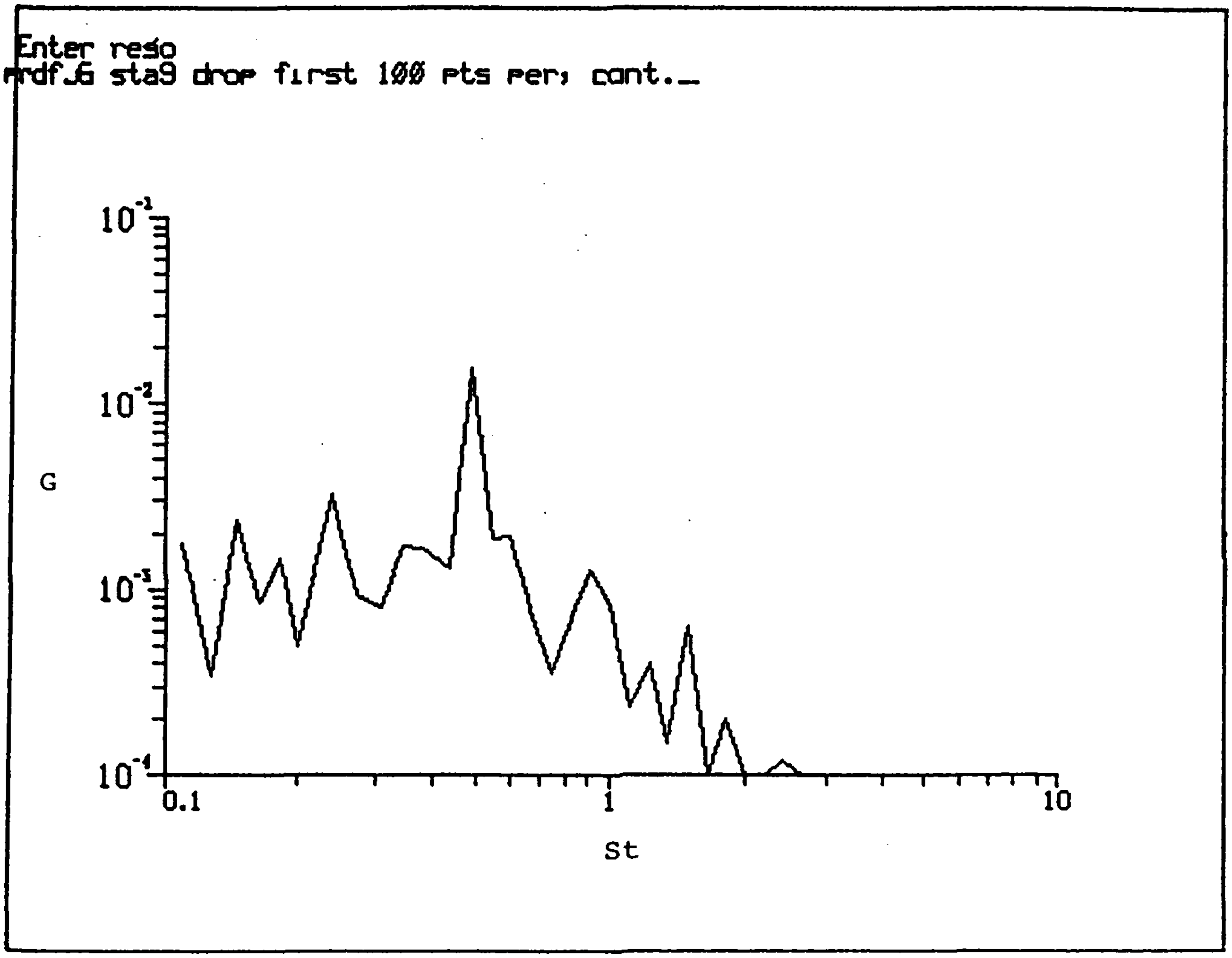


Figure 7.- Variation of Power Spectrum with Strouhal Number (Free Jet).

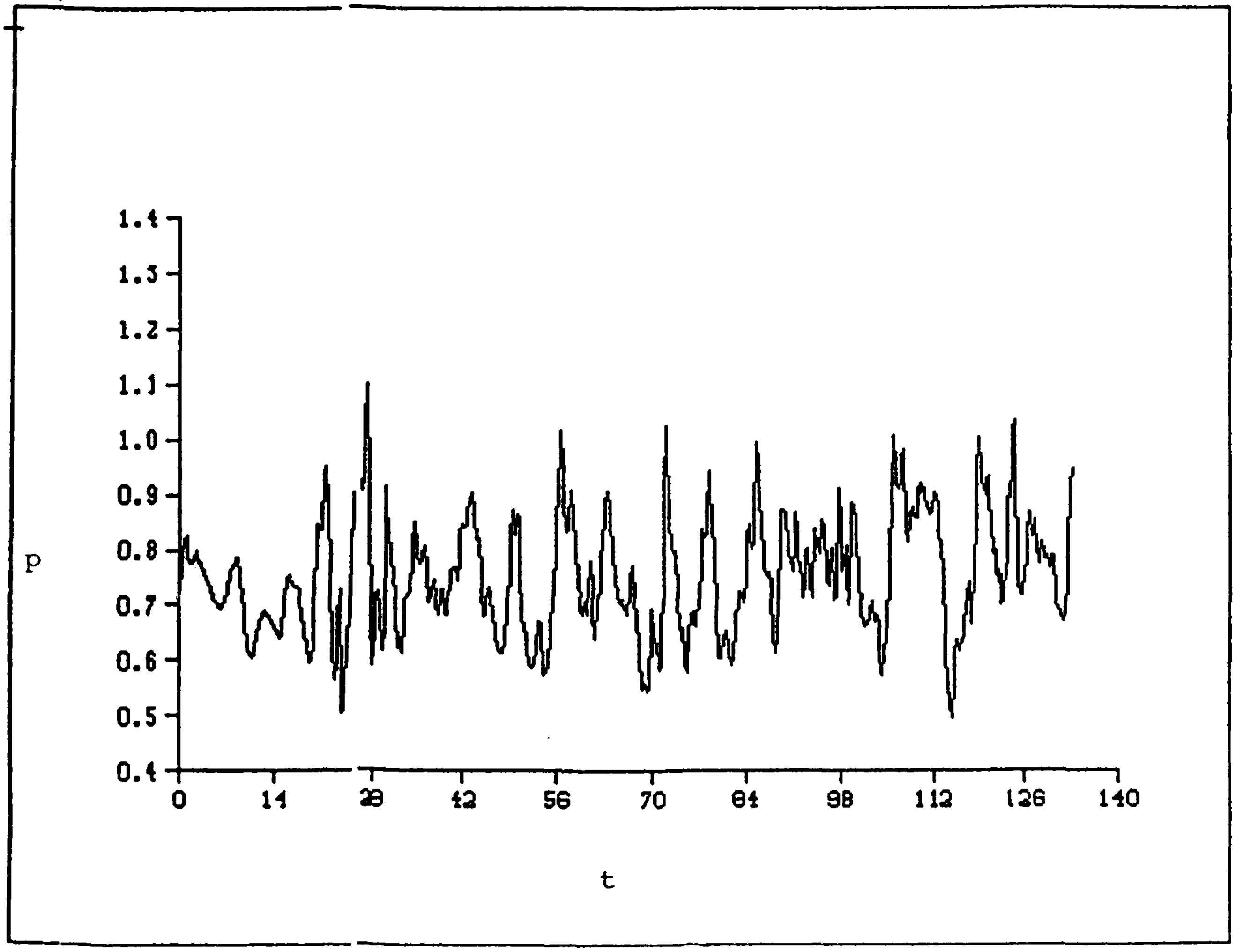


Figure 8.- Variation of Pressure with Time (Impinging Jet).

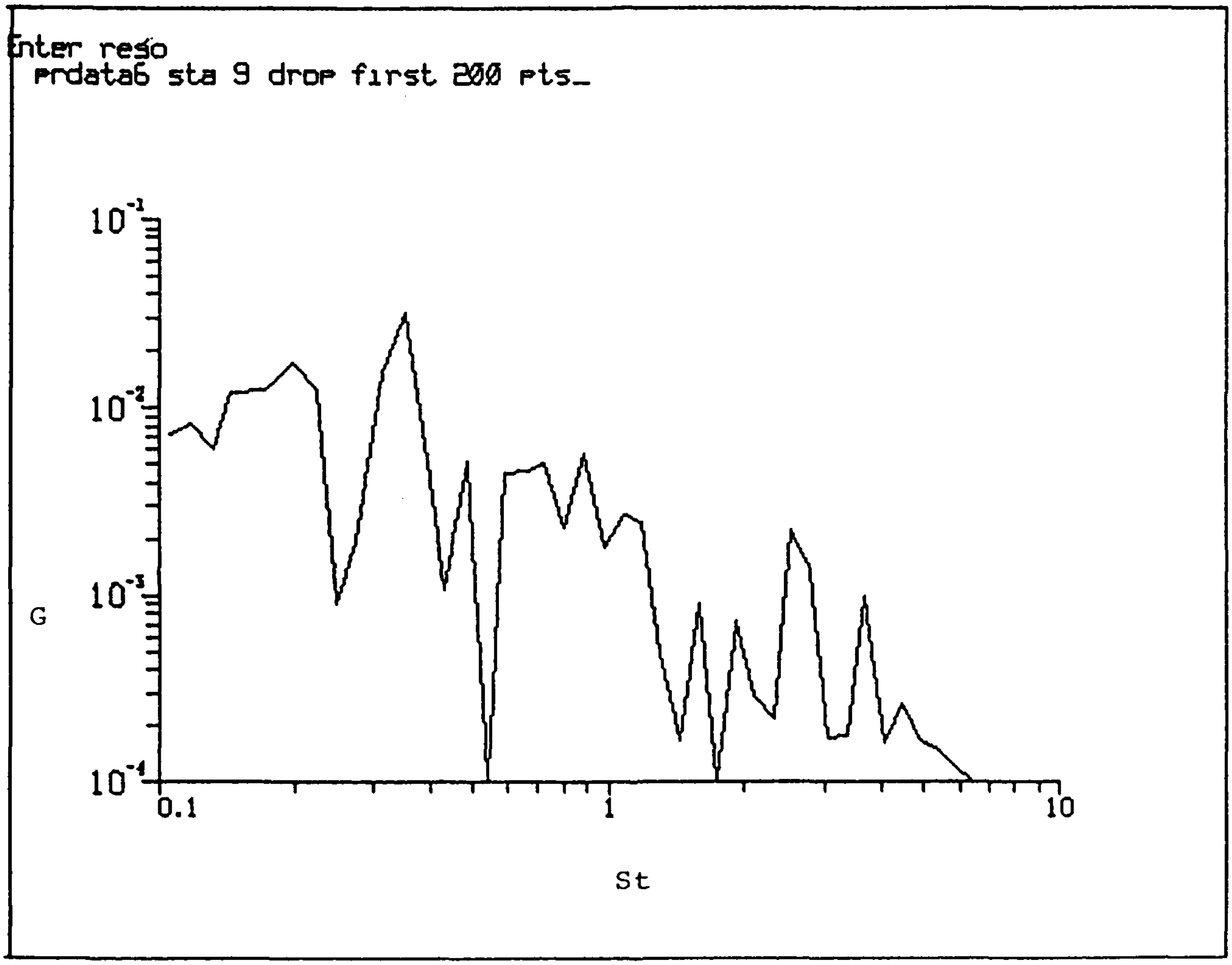


Figure 9.- Variation of Power Spectrum with Strouhal Number (Impinging Jet).

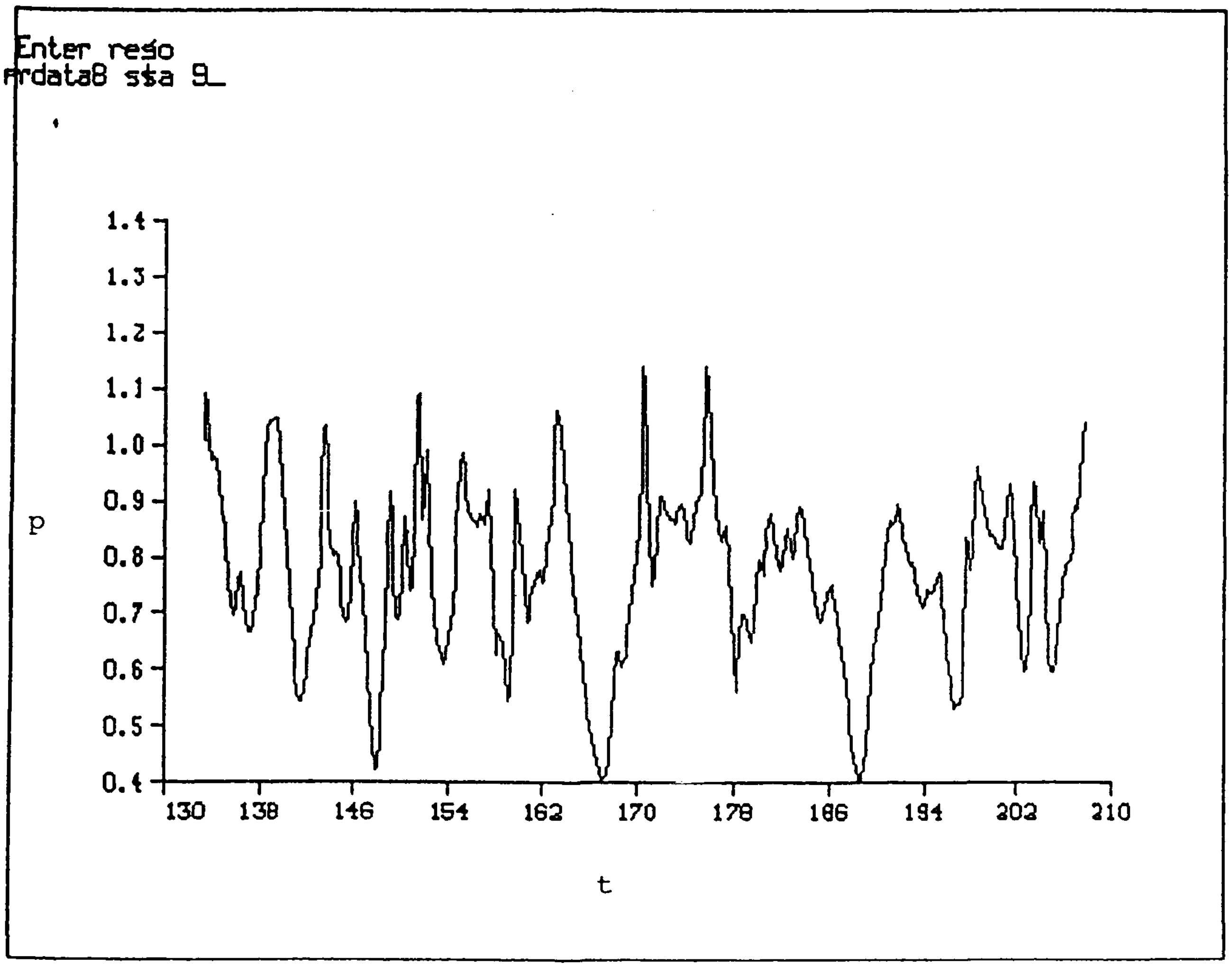


Figure 10.- Variation of Pressure with Time (Modified Impinging Jet).

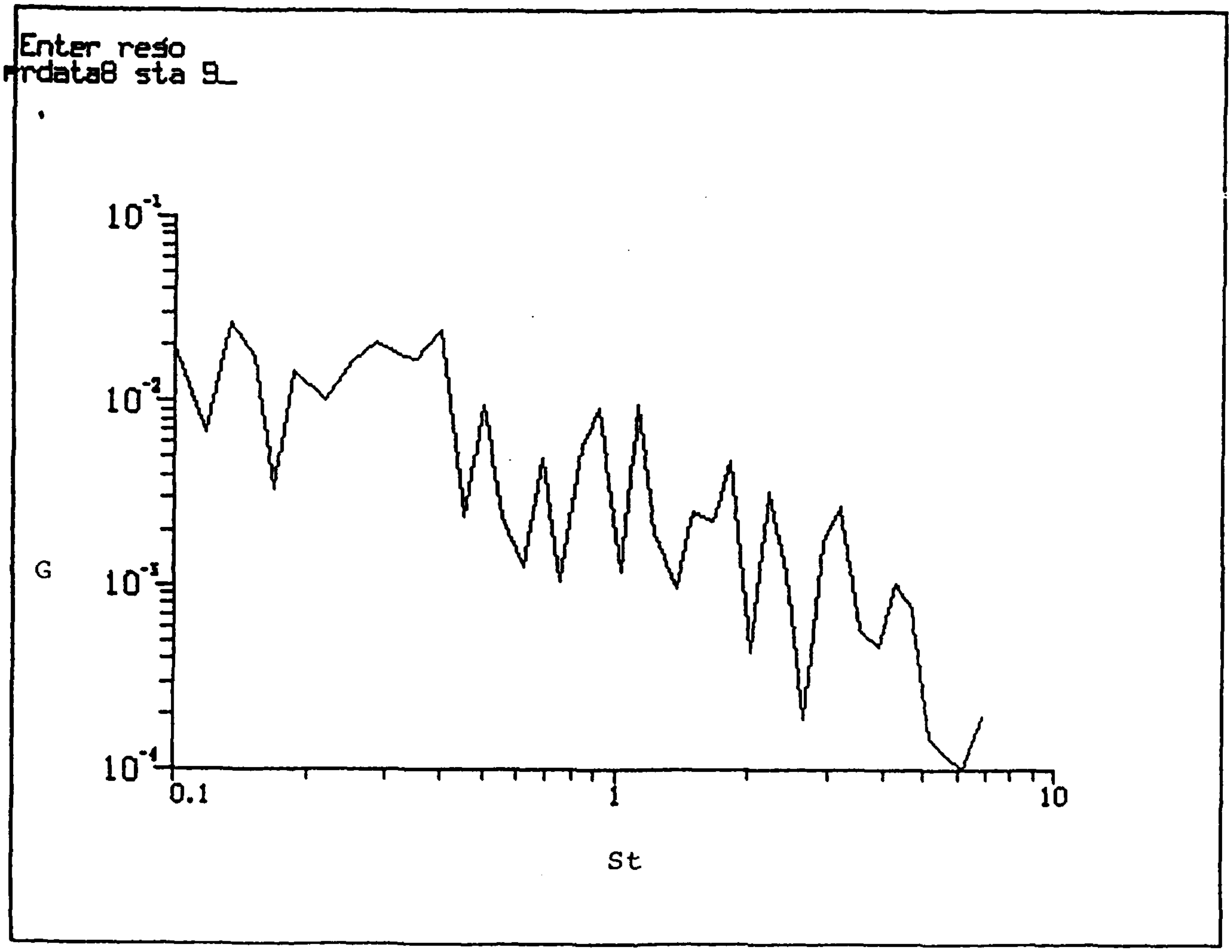


Figure 11.- Variation of Power Spectrum with Strouhal Number (Modified Impinging Jet).

RESEARCH OBJECTIVES

The objective of the present work is to investigate certain complex fluid interactions for impinging jets. These interactions may be unsteady. The investigation uses the techniques of Very Large Eddy Simulation (VLES) of the flow in which the large eddies in the flow are resolved and the smaller eddies modeled. Although computer restrictions do not allow sufficient grid points for a quantitative solution of the problem a qualitative solution, which gives insight into the physical aspects is possible. The problems that have been studied are noted below.

a) Spreading Rate of the Fountain

When two wall jets collide an upwash fountain appears which is an important phenomena in V/STOL aircraft design. It had been found in previous work (Contract F49620-82-C-0031) that the Reynolds averaged Navier Stokes equation would give solutions with approximately one third of the spreading rate observed in experiment. Even Reynolds Stress Transport Models (RSTM), the most advanced turbulence model available, did not resolve this discrepancy between calculation and experiment. Part of the present work is to use the VLES technique to investigate this problem.

b) Effects of Heat

The effects of high temperature in the jet during impingement are investigated to determine the differences between hot and cold jet flows.

c) Reynolds Number Scaling of The Suck Down Effect

It had been observed that the such down effect, caused by entrainment, seemed to be dependent on Reynolds number. Since the Reynolds averaged equations are essentially independent of Reynolds number it was decided to examine the question of Reynolds number dependence using the VLES technique. The difference between a high and low Reynolds number is the range of turbulence scales and this can be modeled by the VLES method.

d) Flow Resonance

It had been observed in experiments in impinging jet flows that a resonant condition could appear in which the large structures in the jet would lock into a resonant frequency. It was decided to attempt to model this phenomena by the VLES technique, based on the assumption that the largest turbulent structures are responsible for the resonance.

ACCOMPLISHMENTS

The VLES method described below used a simple vorticity model for the subgrid scales. A typical turbulent profile was used as input, with its time average approximately equal to the experimental values. The method works because the flows under consideration are dominated by the streamwise velocity components, which have a lower wave number at the turbulent kinetic energy peak than the other components. This allows the use of a coarser computational grid for accuracy that might otherwise be the case.

a) Spreading Rate of the Fountain

In this problem two, two-dimensional wall jets colliding with each other are modeled. At the jet exits a suitable representation of the turbulence is used and this is validated by comparing the computed Reynolds stresses for an isolated wall jet with experimental data. The VLES calculation did produce the increased spreading rate compared with an averaged calculation. The mechanism of the enhanced spreading rate is that eddies of different kinetic energy collide and thus the high energy eddy will push through the opposing flow before being deflected upwards in the fountain. In an averaged calculation all of the colliding eddies have the same energy and hence do not push through the opposing flow but are deflected upwards about the plane of symmetry. This work is reported in Reference 1.

In addition to the above calculation the code was run with a fence at the collision point. Since the fence will stop the high energy eddies at the plane of symmetry it is to be expected that the spreading rate would decrease. This conjecture was supported by the computational results.

As a final case the code was run again with one jet heated to act as a tracer. This calculation supported the explanation of the enhanced spreading rate. In addition it indicated that the heat transfer could not be modeled by gradient diffusion.

b) Effects of Heat

In these calculations a hot jet (1008 deg. K) exhausting into an atmosphere at 288 deg. K with a crossflow is modeled. The main object was to determine the effect of temperature on the shape of the ground vortex. The calculation used the Reynolds averaged equations with a variable density $k-\varepsilon$ turbulence model as a base. The viscosity was temperature dependent using Sutherlands law. Two runs with different temperatures were made, the second calculation being for a jet at ambient temperature. The difference in most of the flow parameters was of the order of 5%. Hence the effects of temperature do not appear to be large.

c) Reynolds Number Scaling of the Suck Down Effects

In these calculations the VLES code for two colliding wall jets was run at three different Reynolds numbers, 20,000, 40,000, 60,000. The grid was chosen so that the filter size in each calculation was the same ratio to the Kolmogorov scale. This does give a Reynolds number effect proportional to $1/Re^2$. In these calculations the mass flux across the boundaries excluding the wall jets is determined. It is found that the entrainment for $Re = 2 \times 10^4$ is approximately 25% lower than that for $Re = 4 \times 10^4$ while at $Re = 6 \times 10^4$ the entrainment is approximately 8% lower than that for $Re = 4 \times 10^4$. The latter change may be due to numerical error. However, it does appear that there is a Reynolds number scaling of the Reynolds number of the order of 10^4. It is not clear whether this is the dominant effect in the discrepancy between large and small scale experiments.

d) Resonance

In these VLES calculations the jet has a Mach number of 0.9 and a height/diameter of 3. Several attempts were made to induce resonance but no definite conclusion was reached. It did appear as if a resonance phenomena was happening in bursts but it is not clear if this is due to numerical or physical aspects of the calculation. A calculation of a free jet did develop a periodic structure of ring vortices which indicates that the method can model large periodic structures. An interesting aspect that did arise in the calculations was the appearance of shock waves near the impingement zone due to the turbulence. These shock waves appeared either at the edge or at the top of the impingement zone.

REFERENCE

1. Childs, R. E., Nixon, D.: Unsteady Three Dimensional Simulation of a VTOL Upwash Fountain, AIAA Paper No. 86-0212, 1986.

LIST OF PUBLICATIONS

1. Childs, R. E., Nixon, D.: Unsteady Three Dimensional Simulation of a VTOL Upwash Fountain, AIAA Paper No. 86-0212, 1986.

2. Childs, R. E., Nixon, D., Kuhn, G. D., Perkins, S. C., Jr.: Abstract for AIAA 25th Aerospace Sciences Meeting, 1987.

PROFESSIONAL PERSONNEL

Dr. David Nixon
(Awarded the degree of Doctor of Science by the Queens University of Belfast, July 1985)

Dr. Robert E. Childs

Dr. Gary D. Kuhn

Mr. Stanley C. Perkins, Jr.

Dr. Richard Cooper (on sabbatical from the Queens University of Belfast)

Prof. Peter Bradshaw (Imperial College, England)

SCIENTIFIC INTERACTIONS

Childs, R. E., Nixon, D.: Unsteady Three Dimensional Simulation of a VTOL Upwash Fountain. AIAA Aerospace Sciences Conference, Reno, Jan. 1986.

Childs, R. E., Nixon, D.: Unsteady Three Dimensional Simulation of a VTOL Upwash Fountain Turbulence. Ground Effects Workshop NASA/Ames Research Center, August 20-21, 1985.

END

1-87

DTIC